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Overview of the state of technique for PV inverters used in low voltage grid-connected PV systems: Inverters below 10 kW

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ABSTRACT

An analysis has been made of the most important electrical parameters related to photovoltaic grid-connected inverters below 10 kW. To achieve this, a compilation of up to 50 manufacturers, various brands and up to 500 different models has been prepared and updated to February 2008. Datasheet and manuals have been compiled, noting down their electrical output and input characteristics. Different and important aspects with respect to performance of some PV grid-installation have been analyzed: the number of different models for values of power; topology option; operational DC parameters range (such as nominal power, maximum power, nominal current, voltage), operational AC parameter range (such as nominal power, maximum power, nominal current, voltage), inverter conversion efficiency vs nominal power and normalized inverter size and weight.

Contents

1. Introduction

Currently the management of energy sources represents a fundamental problem for the development and prosperity of any community. As a result, two major problems exist: diminishing of energy sources and the atmospheric pollution from the residues from conventional sources. Taking both factors into consideration, it can be argued that it is necessary to optimize energy resources through the use of alternative energy sources. The main characteristics of such sources include their renewability and their limited contribution to contamination. Photovoltaic solar energy is in this category and its use has also notably increased in industry over the past few years.

In recent decades there has been an increasing interest in the use of low voltage grid-connected PV systems, conditioned by new incentives from different countries [1,2]. An essential element in those systems is the inverter, that is, the element which converts, in an efficient way, sinusoidal AC current waveform at its output so that it may be connected and synchronized to the utility network [3–14].

2. State of the technique of photovoltaic grid-connected inverters below 10 kW nominal power

In order to carry out this study, a list of 500 models different from the inverter has been compiled. This has been distributed into two groups that are based on their nominal AC power: inverters below 10 kW and inverters up to 10 kW.

With respect to grid inverters there are typically three possible inverter scenarios for a PV grid system: single central inverter,

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multiple string inverters and AC modules. The choice is given mainly by the power of the system. Therefore, AC module is chosen for low power of the system (around 100 W typical) [15]. And a single central inverter or multiple string inverters will be chosen depending on the designer. Technically it is possible to use both topologies.

However, in this article inverters below 10 kW will be analyzed. In this way, 62 brands of different inverters have been compiled, resulting in up to 391 different models.

The following brands were been collated: Aixcon, Alpha, ASP, Atersa, Bahrmann, Beacon, Conergy, Delta Energy, Diehl, Dorfmuller, EAI, Elettronica Santerno, Energetica, Exendis, Fronius, G&H, Gunterman, Hardmeier Elektronik, Ingeteam, Kako, Kostal, Kyocera, Latronic, Leonics, Magnetec, Mastervolt, Mitsubishi, Motech, NKF Electronics, Oelmaier, Omron, Outback Power Systems, Pairan, Philips, Phoenixtec, Power Solutions, PV Powered, Sanyo, SET, Sharp, Siel, Siemens, SMA, Solar Fabrik, Solar Konzept, SolarStocc, SolarWorld, Solectria, Solon, Solutronic, Solwex, Sputnik, Steca, Sun Power, Sunset, Suntechnics, Sunways, Total Energie, Trace, UFE, Victron, Wurth Solergy, Xantrex.

In order to determine the current technology of inverters, up to 50 manufacturers and up to 500 different models were prepared and updated to February, 2008. Datasheet and manuals were compiled noting down their electrical output and input characteristics.

Firstly, seven AC module inverters were found whose power range was between 3.6 and 0.1 kW. Inverters were also analyzed according to transformer options. These can therefore be divided into three groups: 50 Hz LF transformers, 27%, HF transformers, 36%, and transformerless, 37%. As can be deduced from this data, there is not currently a clear tendency in any of the three options, for this power range. However, nowadays the most number of inverters are transformerless inverters, something not usual some years ago. Within of every group FET, IGBT and even Thyristor implementation were found.

Later, different parameters' inverters were analyzed. These are very useful for PV plant designers and can limit the size of the PV array, for instance. Those can fall into two main categories: those that relate to the input inverter and those that concern the output inverter.

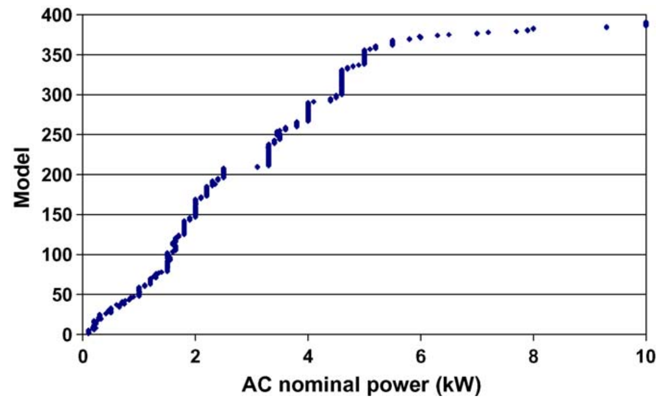

Fig. 1. Distribution of the models in function to AC nominal power (kW).

3. Output electrical parameters

Output electrical inverter parameters relate to the AC output inverter. Different output parameters such as nominal power, nominal power, Pnominal, maximum power, PMax, nominal current, Inom, maximum current, Imax, output voltage, Voutput, Type (Phases) and frequency, Freq. (Hz), have been analyzed [16].

From this data it is possible to see the distribution in function on AC nominal power (kW), Fig. 1. In addition, Fig. 2 shows the distribution for every transformer option. As can be observed, the distribution is very homogeneous.

This data also allows us to deduce that within this power range, there are 76 different values of AC nominal power that oscillate between 0.1 and 10 kW. The number of models for each value of nominal AC power is represented in Fig. 3. In addition, from Fig. 4, it can be seen that the most of the inverters studied stay between 0 and 5 kW (in fact 91% of them do so) It can also be inferred that the maximum number of models for the same power corresponds to

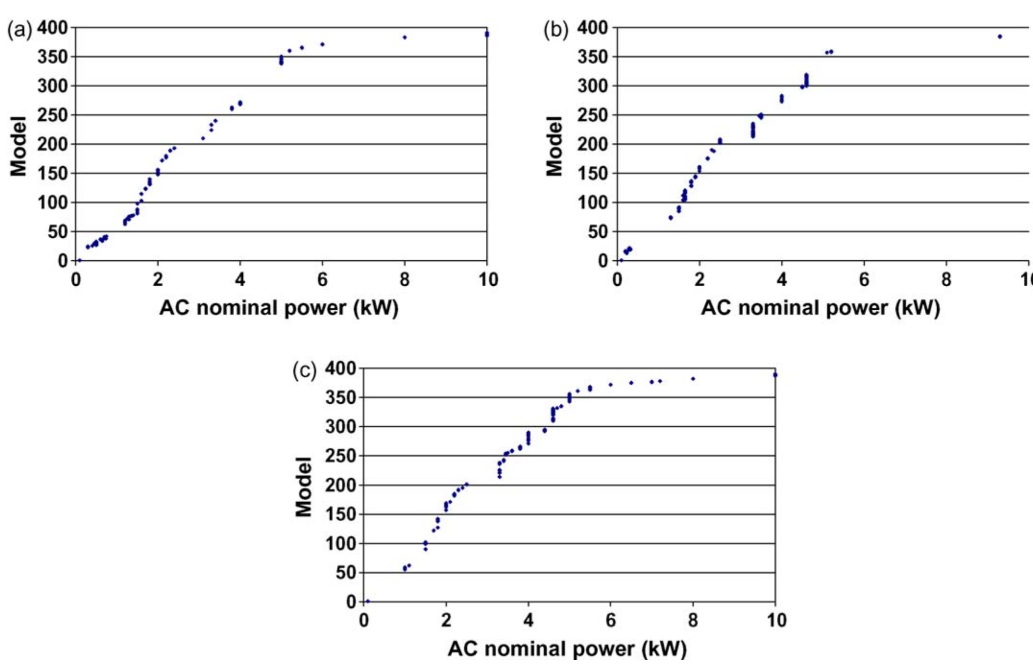

Fig. 2. (a) Distribution of the models in function to AC nominal power (kW) for inverters with LF transformer. (b) Distribution of the models in function to AC nominal power (kW) for inverters with HF transformer. (c) Distribution of the models in function to AC nominal power (kW) for inverters without transformer.

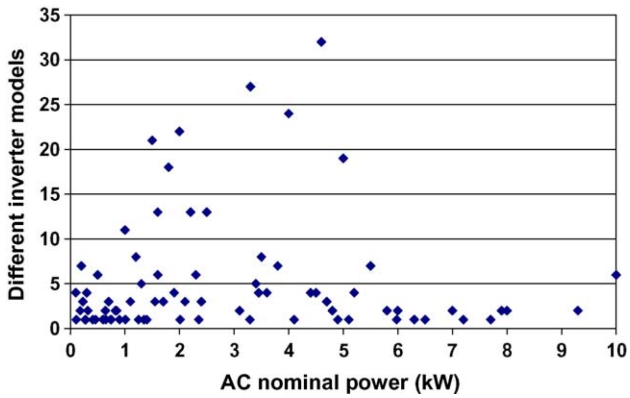

Fig. 3. Number of the different models vs AC nominal power (kW).

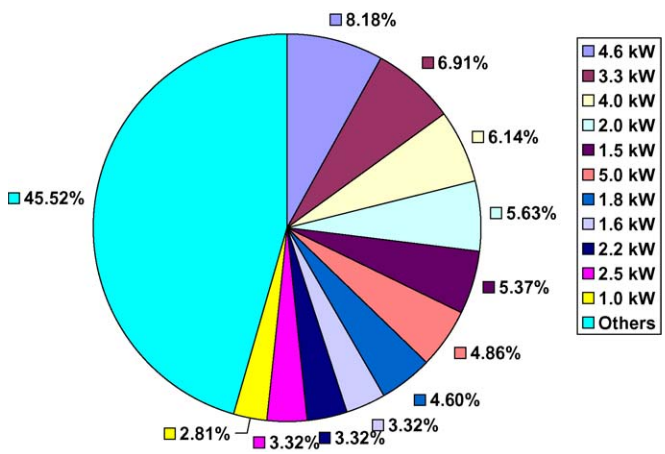

Fig. 4. Distribution of the number of the different models vs AC nominal power (%).

4.6 kW, with 32 models (which represents 8.18%) followed by the inverters of 3.3 kW (6.91%) and 4.0 kW (6.14%). On the other hand, inverters below 3 kW represent 53.7% whilst inverters below 2 kW constitute 42.96% of total inverters. Additionally, in the same figure it can be seen that the strip between 5 and 10 kW is sufficiently depopulated. What is more, the fact that there is a smaller number of inverter models, with respect to the 62 different powers available up to 5 kW, is significant.

After this, the next analysis was of the inverter distribution with respect to the number of phases (single-phase/three-phase) and the operation frequency (50/60 Hertz). Results are shown in Table 1, where it can be observed that 92.8% corresponds to single-phase inverters, as was expected for this range of power. Within the single-phase inverters, 92.3% are inverters that operate up to 50 Hz. As was foreseeable, the three-phase inverters that are used for big power, in this case correspond to inverters with power up to 4 kW (except for the model of 2.2 kW). Next 20 of the 26, three-phase inverters (of up to 5 kW)are found to be three-phase, and to operate mainly at 50/60 Hz. This detail does not agree with the great majority of cases where 73% of single-phase inverters operate exclusively at 50 Hz. In addition, it can be noted that 60 Hz three-phase inverters were not found.

With respect to output voltage, eight different voltages were found: 115, 120, 132, 208, 230, 240, 260, 400 V. However, the output voltage most used was 230 V (in a 87% of them).

Table 1
Inverter distribution with respect to number of phases.

		# Inverters
Single-phase		365
	50 Hz	268
	50–60 Hz	69
	60 Hz	28
Three-phase		26
	50 Hz	9
	50–60 Hz	17
	60 Hz	0

4. Input electrical parameters

Input electrical parameters relate to DC input inverter [17]. They are as follows: the maximum input operating voltage, the minimum voltage for obtaining the maximum power point and the maximum voltage for obtaining the maximum power point. These parameters are totally relating to sizing of the PV array.

According to maximum voltage (that is the maximum DC input voltage permitted in the input of the inverter) it can be seen in Fig. 5 that the maximum voltage range is very broad, between 25 and 900 V. This means that the same number of PV array of modules for all inverters cannot always be installed. In addition, it has to be taken into account that nowadays the market is generally focused on obtaining more powerful modules. As well, there is an increasing emphasis on greater value of open circuit voltage and maximum voltage point. More often than not it is very difficult find them (and more expensive).

In addition, it can be deduced that there is no relation between maximum voltage and AC nominal power of inverter. That is to say, there are inverters with a high maximum voltage and low AC nominal power. Everything depends on the topology used in every inverter.

On the other hand, it has to be taken into account that in Europe single-phase inverters operates at 230 Vac (or 325 Vpeak) grid voltage. Consequently, if the maximum voltage is below 325 Vpeak (230 Vac) the inverter will operate as boost inverter. On the other hand if the inverter operates up to 325 Vpeak will operate as buck inverter. In this way, it can be seen that from inverters chosen 101 (25.8%) lays like input voltage below 325 V. That means that right now the most of inverters are boost inverters.

Additionally the range of maximum voltage was analyzed for inverters with different options of transformers: LF, HF and transformerless, Fig. 6a–c, respectively. As can be viewed the ranges are very similar for inverters with LF transformer and transformerless inverters (50–900 V). But that range diminishes lightly for inverters with LF transformer (50–600 V). As well, it can be deduced that there is no relation between maximum voltage and different options of transformers of inverter.

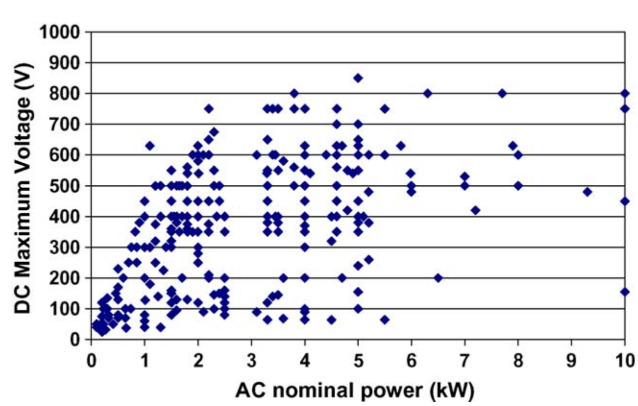

Fig. 5. DC maximum voltage of inverters vs. AC nominal power (kW).

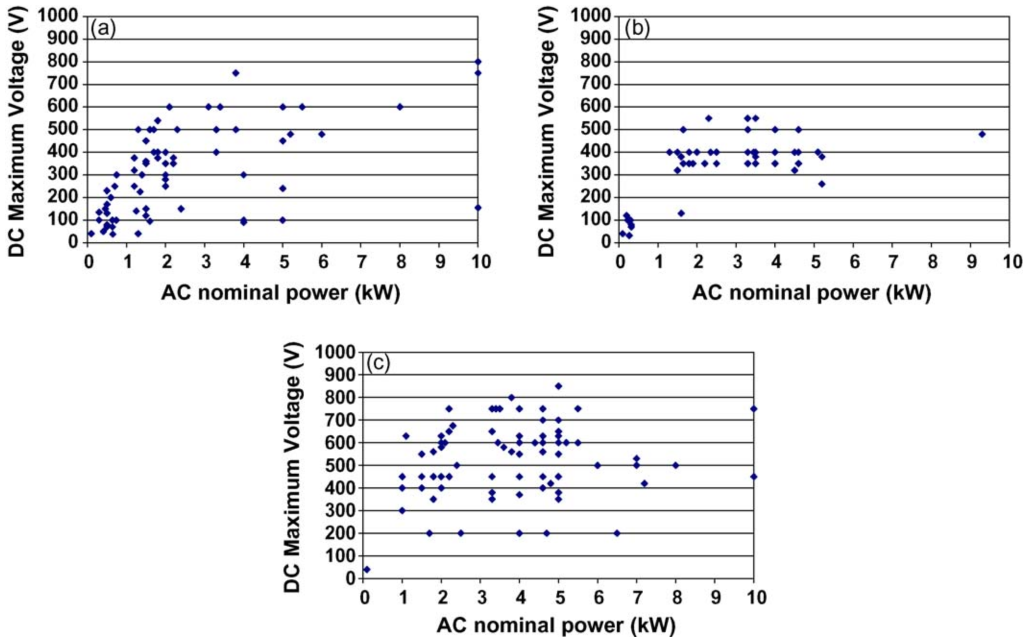

Fig. 6. (a) DC maximum efficiency for inverters with LF transformers; (b) DC maximum efficiency for inverters with HF transformers; (c) DC maximum efficiency for inverters with transformerless.

Another interesting parameter analyzed is the maximum power point tracking implemented by grid-inverters [18–20]. Firstly, it can be proved that nowadays all inverters have a module which seeks the maximum power point (MPP) of the PV generator. Because if inverter does not operate in the maximum power point (MPP) the installation will present production loss. However the manufacturers do not give the MPP algorithm used (or at least their name).

That MPP is characterized by a current and voltage values. So, in order to be versatile one can connect different combination of PV array to inverter. Thus for every inverter there will be a range voltage for which the maximum power point tracking is suitable. That range is defined between the minimum and maximum and maximum MPP voltage.

From our study of inverters, it can be seen that the minimum MPP voltage fluctuates between 14 and 600 V, Fig. 7. At the same time the maximum voltage fluctuates between 50 and 850 V, Fig. 8. Also Fig. 9 shows the difference between maximum and minimum VPP voltage vs AC nominal power. As can be seen there is a lot of heterogeneity between them.

As well, other parameters such as efficiency have been analyzed. The electrical conversion efficiency is defined as $\eta_{\text{inv}} = P_{\text{AC}}/P_{\text{DC}}$, where P_{AC} is the inverter output power and P_{DC} is the inverter input power. This parameter is strongly important because “manages” the energy into the grid. In general, efficiency has been increasing continuously during the last few years. Such efficiency (%) varies with the photovoltaic output power (W), Fig. 10.

Related to efficiency, two parameters were found in the catalogues and manuals: the efficiency (although in fact is the maximum efficiency) and the European Efficiency.

The maxima efficiency (%) is the maximum value found for all range of power (W), for every inverter. It is a value that by itself offers very little information. Because, it is not the same to have a high maximum efficiency for a low power (%) than for a high power (%). But in catalogues and manual such value is given without explaining for what power (%) has been obtained.

In Fig. 11 it can be observed that the efficiency range oscillates between 88.9 and 98%. Moreover, it is noticed that there is no relation with the AC nominal power (kW) because one can found low values for high AC nominal power.

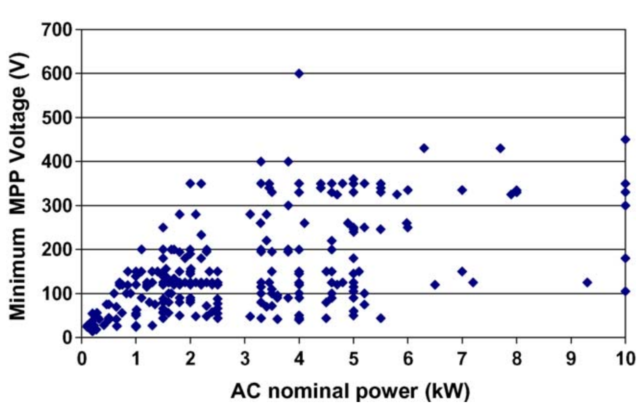

Fig. 7. Minimum MPP voltage (V) vs AC nominal power (kW).

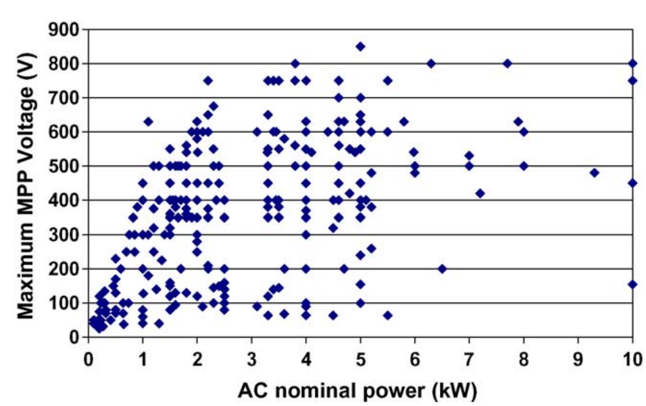

Fig. 8. Maximum MPP voltage (V) vs AC nominal power (kW).

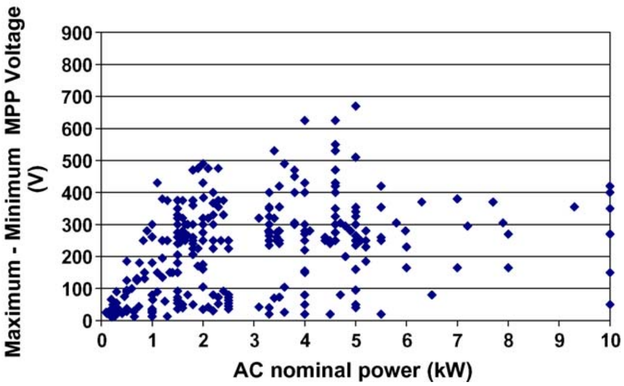

Fig. 9. Difference between maximum and minimum MPP voltage (V).

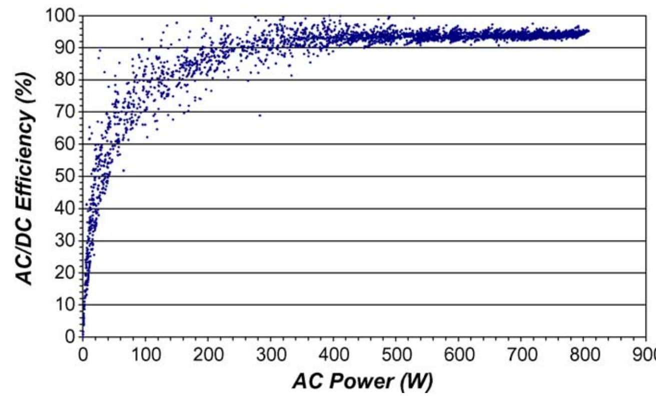

Fig. 10. Typical experimental AC/DC efficiency (%) with respect to AC power (W), for a generic grid-connected inverter.

On the other hand, the influence of the use or not of transformers in the inverters has been analyzed. From Fig. 12a–c can be viewed that for inverters with LF and HF transformer the maxima efficiency reached is 96%. However for transformerless inverters the maxima efficiency reached is 98%, although only for some models, even for high values of power. However, it is noticed to mention that 88% is reached even for transformerless inverters. It means that depending of topology, control and transformer option chosen maxima efficiency close to 98% can be reached.

Alternatively, the relationship between the minimum MPP (maximum power point) voltage (V) and the maximum efficiency

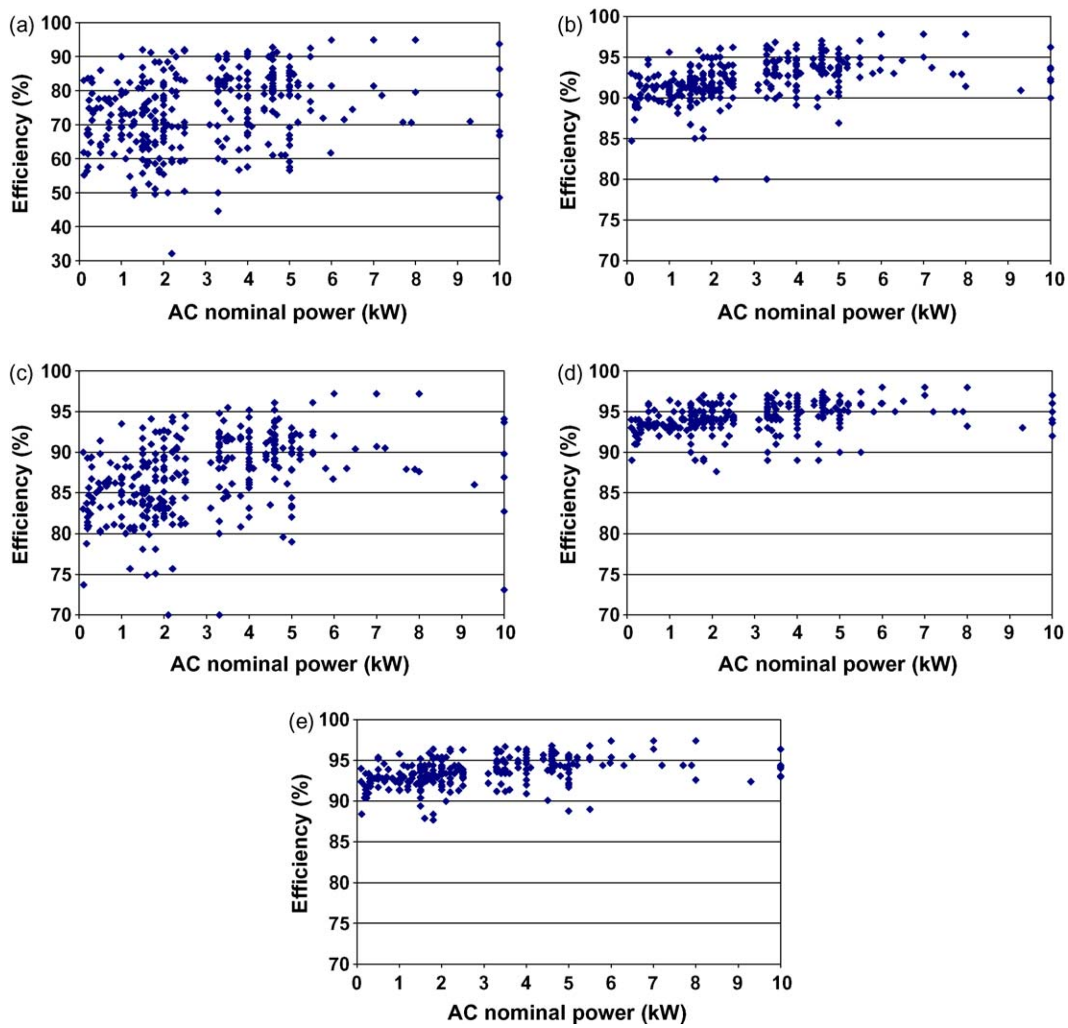

Fig. 11. (a) Efficiency vs AC nominal power (kW) for all inverters with 5% of AC nominal power. (b) Efficiency vs AC nominal power (kW) for all inverters with 10% of AC nominal power. (c) Efficiency vs AC nominal power (kW) for all inverters with 20% of AC nominal power. (d) Efficiency vs AC nominal power (kW) for all inverters with 60% of AC nominal power. (e) Efficiency vs AC nominal power (kW) for all inverters with 100% of AC nominal power.

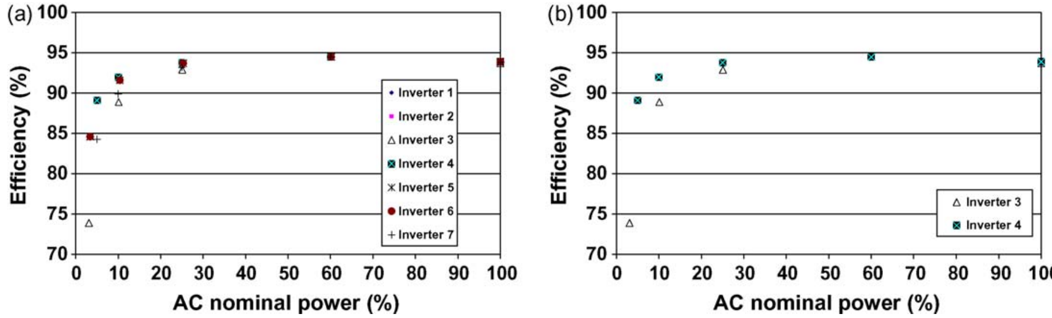

Fig. 12. (a) Efficiency vs AC nominal power (%) for six inverters with 4.6 kW. (b) Efficiency vs AC nominal power (%) for two of the six inverters from (a).

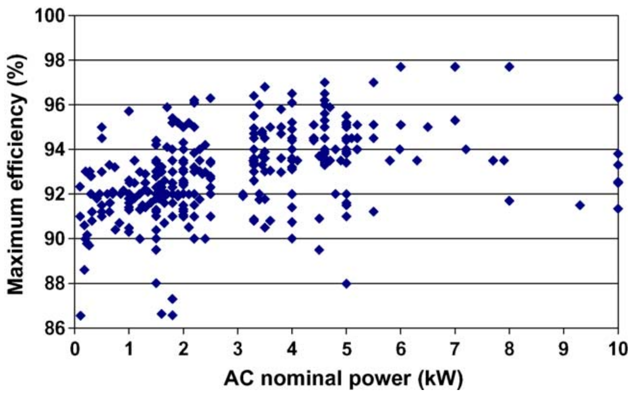

Fig. 13. Maximum efficiency (%) vs. AC nominal power (kW).

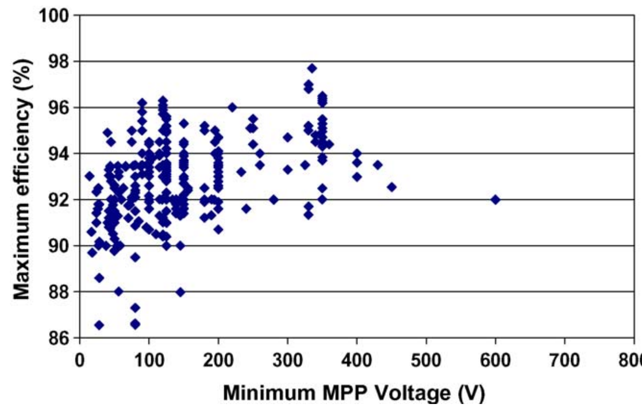

Fig. 15. Maximum efficiency (%) vs minimum MPP voltage (V).

(%) has been analyzed, Fig. 13. In this way, for minimum MPP voltage below 325 V, it can be noticed how the range of the efficiency (between 86 and 96%) is the same for inverters with LF and HF transformer, Fig. 14a and b. However this range is a little bit different (between 88 and 96%) for transformerless inverters although in all inverters 96% is reached, Fig. 14c. That means that there is no relation between maximum efficiency and PV minimum voltage (V).

Moreover the efficiency vs maximum input voltage has been analyzed, Fig. 15a and b. From them the efficiency for boost inverters fluctuates between 89 and 97 (%) and for buck inverters between 91 and 98 (%). However, as can be observed the range is a little bigger for buck inverters.

Another representative efficiency which is used to compare different inverters, is the so-called 'European efficiency', η_{EU} [21], [22]. It was introduced in 1991 [4]. It is described in function of the

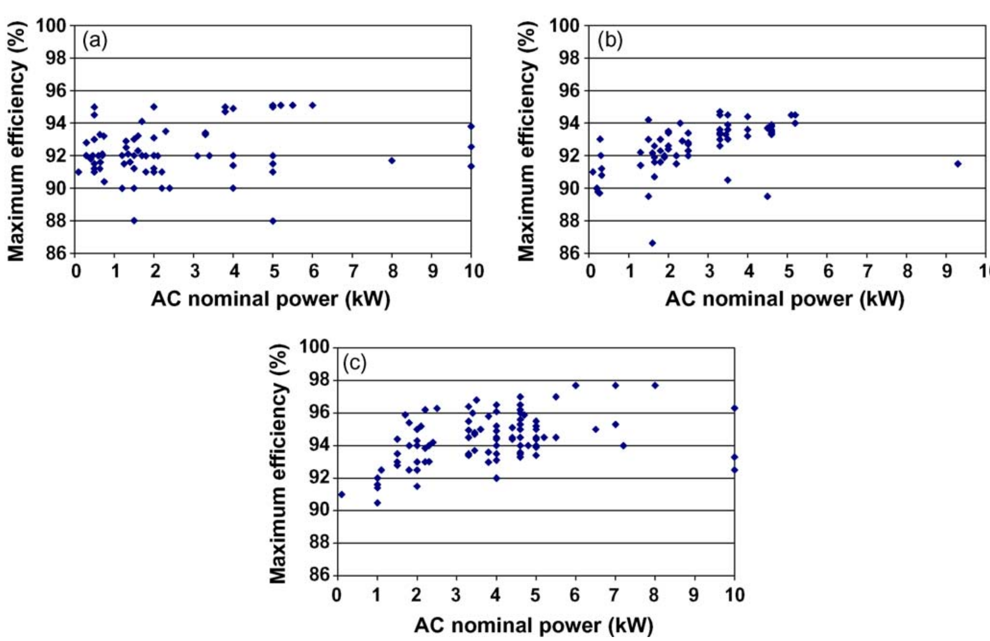

Fig. 14. (a) Maximum efficiency for inverters with LF transformers. (b) Maximum efficiency for inverters with HF transformers. (c) Maximum efficiency for inverters with transformerless.

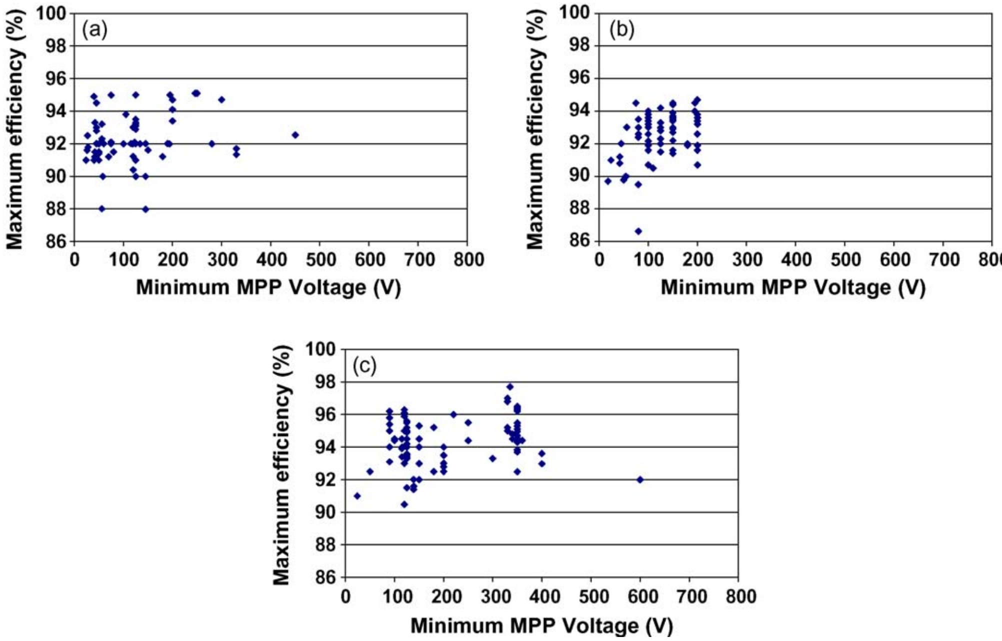

Fig. 16. (a) Maximum efficiency vs Minimum MPP voltage for inverters with LF transformers. (b) Maximum efficiency vs minimum MPP voltage for inverters with HF transformers. (c) Maximum efficiency vs minimum MPP voltage for inverters with transformerless.

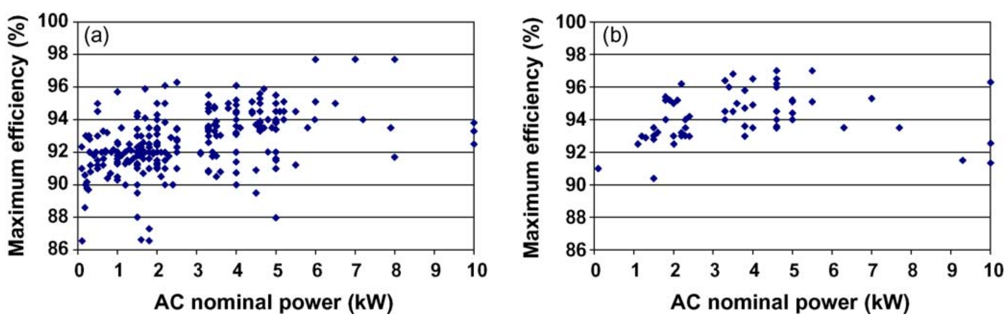

Fig. 17. (a) Maximum efficiency vs AC nominal power (kW), for buck inverters. (b) Maximum efficiency vs AC nominal power (kW), for boost inverters.

efficiency at defined percentage values of nominal AC power as Eq. (1), where, as example, $\eta_{10\%}$ is the efficiency operating at 10% of the inverter nominal power.

$$\eta_{\mathrm{EU}} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.1\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%} \quad (1)$$

Nevertheless, the weighting factors refer to the irradiance distribution in north-western Germany at that time. Therefore, they are not necessarily representative for all parts of Europe, especially for southern Europe. However, today it is a well established value for a quick comparison of conversion efficiency of inverters. In addition, it should be mentioned that η_{EU} can be an appropriate efficiency descriptor for PV systems with fixed angle structures for a general climate conditions. But, both local climatic conditions and type of tracking can influence the energy efficiency inverter.

According to Fig. 16 European efficiency fluctuates between 86.55 and 97.7%. Although apparently there is no clear relation with the nominal power, it seems that the values of such efficiencies increase, in a certain way, with the nominal power, although not in very homogenous way.

In addition the influence of the use or not of transformers in the inverters has been analyzed too. So, European efficiencies above 96% have not been found except for some brands of transformerless inverters which reach 98%. However also 88% values can be found for that type of inverters.

In addition the relationship between European efficiency and the boost and buck inverters was analyzed, Fig. 17a and b.

The range found of the European efficiency for inverters with minimum MPP voltage below 325 V was between 89 and 97. On the other hand this range for inverters up 325 is 93–98.

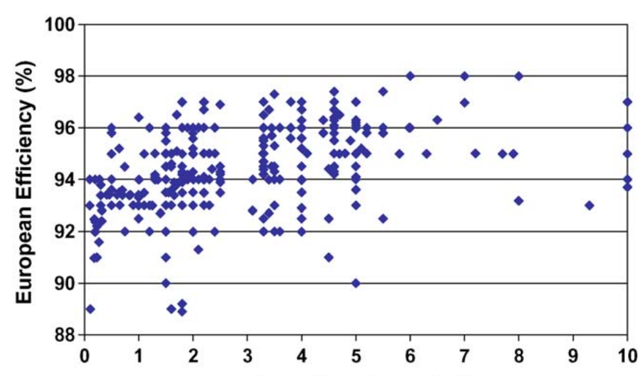

Fig. 18. European efficiency (%) vs AC nominal power (kW).

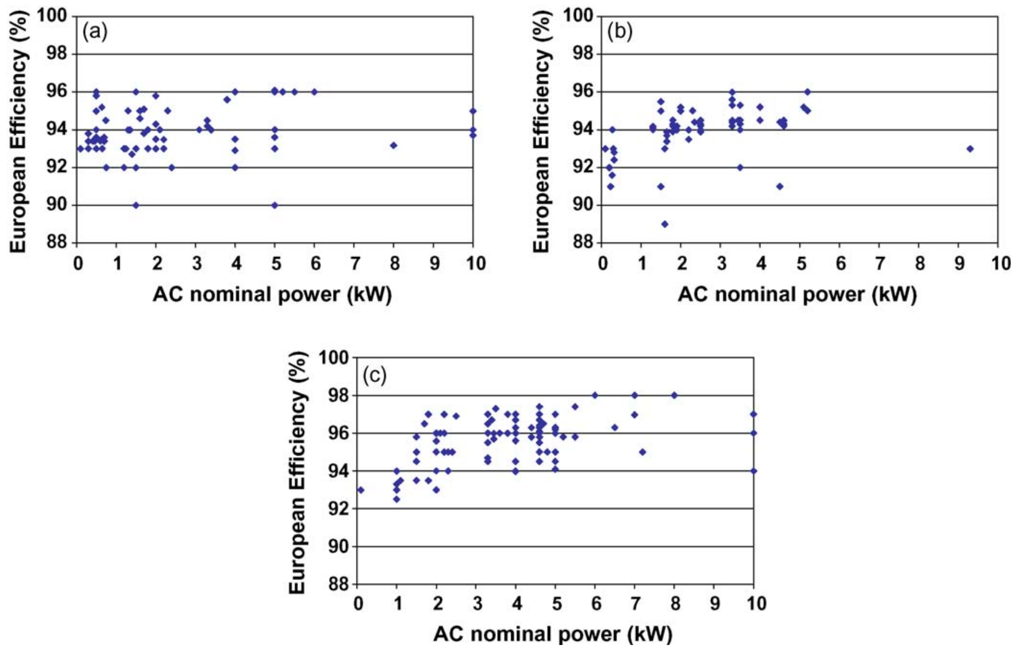

Fig. 19. (a) European efficiency (%) vs AC nominal power (kW) for inverters with LF transformer. (b) European efficiency vs AC nominal power (kW) for inverters with HF transformer. (c) European efficiency vs AC nominal power (kW) for inverters with transformer.

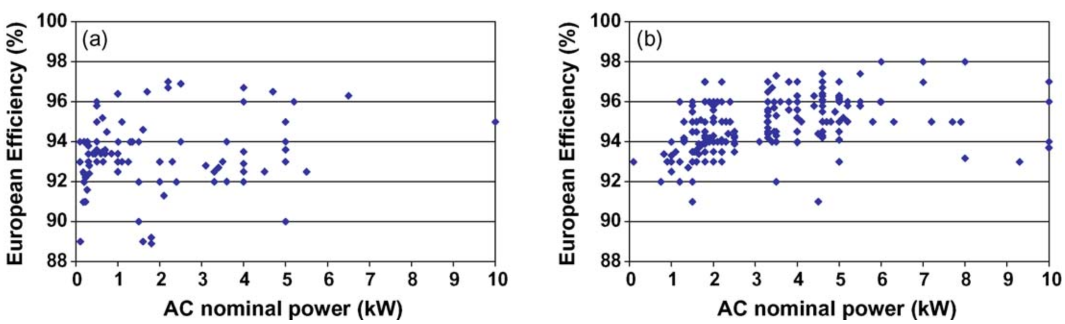

Fig. 20. (a) European efficiency (%) vs AC nominal power (kW) for buck inverters. (b) European efficiency (%) vs AC nominal power (kW) for boost inverters.

5. Other parameters

As well, other parameters such as volume and weight have been analyzed. In this way, normalized volume inverters have been analyzed, see Fig. 18. Next, it can be observed how a large majority of inverters have a volume/power ratio below 20. Thus, only 60 of them, 15.3%, have an upper ratio. Also it can be inferred that volume/power ratio is not proportional to the nominal output power.

In addition, normalized weight has been analyzed for every inverter, Fig. 19. This data shows that there is great heterogeneity

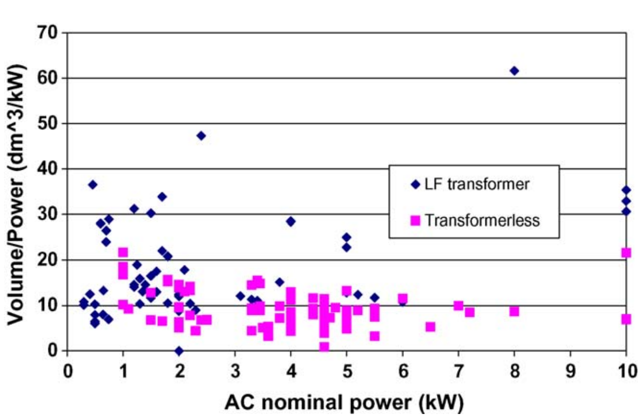

Fig. 21. Volume/power (dm^3/kW) vs AC nominal power (kW) for inverters with LF transformer and without transformer.

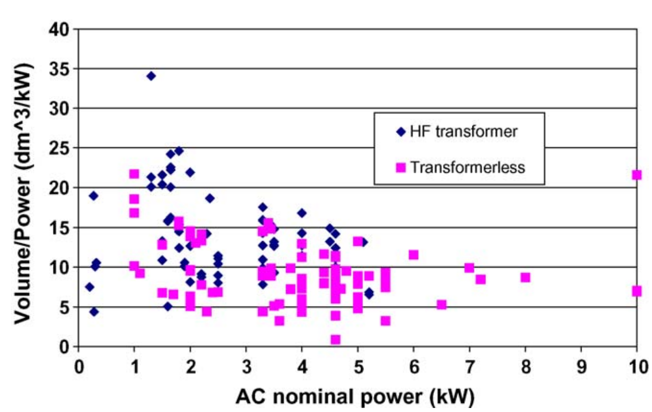

Fig. 22. Volume/power (dm^3/W) vs AC nominal power (kW) for inverters with HF transformer and without transformer.

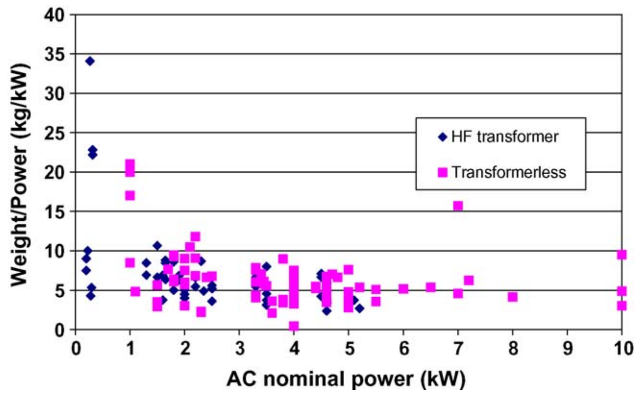

Fig. 23. Weight/power (kg/kW) vs AC nominal power (kW) for inverters with HF transformer and without transformer.

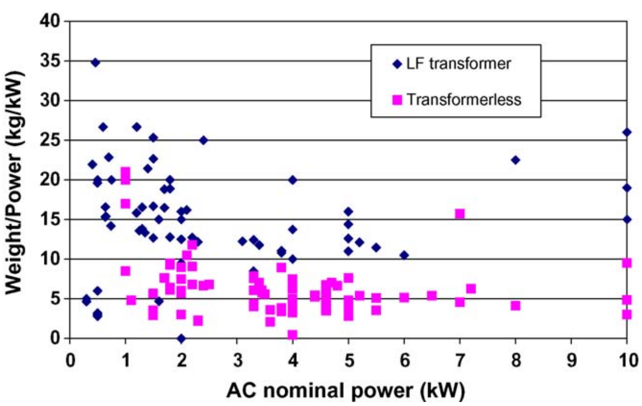

Fig. 24. Weight/power (kg/kW) vs AC nominal power (kW) for inverters with HF transformer and without transformer.

among them. Thus, there are inverters with lighter and less voluminous LF transformers than transformerless inverters. That means that contrary to common knowledge, it is not true to say that an inverter with an LF transformer has more volume and weight than an inverter with HF transformer, and at the same time an inverter with an HF transformer has more volume and weight than a transformerless inverter (Figs. 20–24).

6. Conclusions

According to the obtained results the following conclusions can be made: different ranges of nominal AC power have been found, between 0.1 and 10 kW. The AC nominal power inverter most used was 4.6 kW, that is for 32 models, 8.18% of the total inverters; nominal AC power inverters below 2 kW representing 42.96%. Likewise, it has been possible to verify that 92.8% of the studied inverters are single-phase, which was expected for this power range. And most of inverters are boost inverters.

In addition, regarding the efficiency, the evolution of the efficiency vs power hardly ever is given in manuals and catalogues. Instead of two efficiencies values are given by manufacturers: maximum efficiency and European efficiency. Regarding maximum efficiency, it is a value that by itself offers very little information because is not given for what value has been obtained. However, it has been possible to find that maximum efficiency oscillates between 88.9% and 98%. The values of these efficiencies are increased, more or less, with the nominal power, although not in a very homogenous way. Also, it has been proven that the maximum efficiency does not depend on transformer options of inverter.

On the other hand, the European efficiency is a parameter whose weighting factors refer to the irradiance distribution in north-western Germany. But it varies according to local climatic conditions and type of tracking used. Their values fluctuate between 86.55 and 97.7%. Although apparently there is no clear relation with the nominal power, it seems that the values of such efficiencies increase, in a certain way, with the nominal power, although not in very homogenous way. Again, there is no relation to transformer option used by every inverter.

In addition, it has been possible to corroborate that the normalized volume and weight is very heterogeneous. Finally, it has been verified that three different topologies exist: inverters with a transformer of LF, a transformer of high frequency and inverters without a transformer, representing 27, 36 and 37%, respectively. These numbers confirm the boom that inverters without transformers have been experiencing in recent years. As well, against common knowledge, it is not true to say that an inverter with an LF transformer has more volume and weight than an inverter with HF transformer, and at the same time an inverter with an HF transformer has more volume and weight than a transformerless inverter.

Acknowledgments

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